

Deformation and weak decay of Λ hypernuclei

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We use the self-consistent mean-field theory to discuss the ground state and decay properties of Λ hypernuclei. We first discuss the deformation of Λ hypernuclei using the relativistic mean-field (RMF) approach. We show that, although most of hypernuclei have a similar deformation parameter to the core nucleus, the shape of ^{28}Si is drastically altered, from oblately deformed to spherical, if a Λ particle is added to this nucleus. We then discuss the pionic weak decay of neutron-rich Λ hypernuclei using the Skyrme Hartree-Fock + BCS method. We show that, for a given isotope chain, the decay rate increases as a function of mass number, due to the strong neutron-proton interaction.

Keywords: Nuclear deformation, mean field theory, pionic decay.

1. Introduction

The self-consistent mean-field method has been a standard approach to the description of ground state properties of atomic nuclei.¹ It has been extensively applied also to hypernuclei,^{2–5} in which the mass number dependence of Λ binding energy has been successfully reproduced, from a light nucleus $^{12}_{\Lambda}\text{C}$ to a heavy nucleus $^{208}_{\Lambda}\text{Pb}$.

In this contribution, we employ the self-consistent mean-field approach to discuss the structure and decay of Λ hypernuclei. In the first part, we discuss the deformation of Λ hypernuclei.⁶ It has been well known that many open-shell nuclei are deformed in the ground state. By allowing the rotational symmetry to be broken in the mean-field potential, the mean-field theory provides an intuitive and transparent view of the nuclear deformation.¹ Recently, the deformation property of Λ hypernuclei has been explored in a broad mass region using the non-relativistic Skyrme Hartree-Fock method.⁷ Here we carry out a similar study using the relativistic mean field (RMF) method as an alternative choice of effective NN and $N\Lambda$ interactions.

In the second part, we discuss the weak decay of neutron-rich Λ hyper-

nuclei. Neutron-rich nuclei are one of the current topics in nuclear physics. In connection to hypernuclear physics, there have been discussions on an extension of neutron-drip line as a consequence of an additional Λ particle.^{8,9} It has been well known that, in finite nuclei, the mesonic (pionic) decay, $\Lambda \rightarrow N\pi$, is largely Pauli-suppressed as the mass number increases, and the non-mesonic decay, $\Lambda N \rightarrow NN$, is the dominant decay mode.^{10,11} However, it has not been known well how the pionic decay mode is suppressed as the neutron number increases for a fixed value of proton number. Here we address this question for relatively light neutron-rich hypernuclei using the non-relativistic Skyrme Hartree-Fock method.

2. Deformation of Λ hypernuclei

Let us first discuss the deformation of Λ hypernuclei.⁶ In the RMF approach, nucleons and a Λ particle are treated as structureless Dirac particles, interacting through the exchange of virtual mesons, that is, the isoscalar scalar σ meson, the isoscalar vector ω meson, and the isovector vector ρ meson. The photon field is also taken into account to describe the Coulomb interaction between protons. The effective Lagrangian for Λ hypernuclei may be given as^{3,8}

$$\mathcal{L} = \mathcal{L}_N + \bar{\psi}_\Lambda [\gamma_\mu (i\partial^\mu - g_{\omega\Lambda}\omega^\mu) - m_\Lambda - g_{\sigma\Lambda}\sigma] \psi_\Lambda, \quad (1)$$

where ψ_Λ and m_Λ are the Dirac spinor and the mass for the Λ particle, respectively. Notice that the Λ particle couples only to the σ and ω mesons, as it is neutral and isoscalar. \mathcal{L}_N in Eq. (1) is the standard RMF Lagrangian for the nucleons.

We solve the RMF Lagrangian (1) in the mean field approximation. The variational principle leads to the Dirac equations for the nucleons and the Λ particle, and the Klein-Gordon equation for the mesons. We solve these equations iteratively until the self-consistency condition is achieved. For this purpose, we modify the computer code **RMFAXIAL**¹² to include the Λ particle. The pairing correlation among the nucleons is also taken into account in the constant gap approximation.

With the self-consistent solution of the RMF equations, we compute the intrinsic quadrupole moment of the hypernucleus,

$$Q = \sqrt{\frac{16\pi}{5}} \int d\vec{r} [\rho_v(\vec{r}) + \psi_\Lambda^\dagger(\vec{r})\psi_\Lambda(\vec{r})] r^2 Y_{20}(\hat{\vec{r}}), \quad (2)$$

from which we estimate the quadrupole deformation parameter β_2 .

Figure 1 shows the deformation parameter for the ground state of Si isotopes obtained with the NL3 parameter set.¹³ The dashed line is the

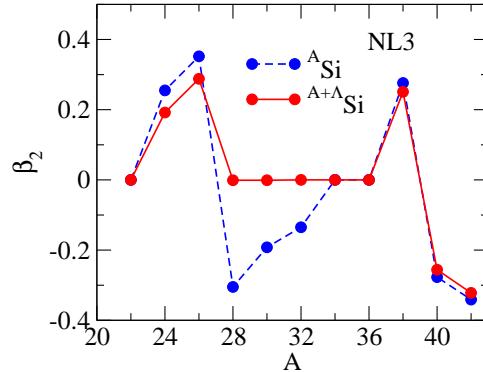


Fig. 1. Quadrupole deformation parameter for Si isotopes obtained with the RMF method with the NL3 parameter set. The dashed line is the deformation parameter for the core nucleus, while the solid line is for the corresponding hypernucleus.

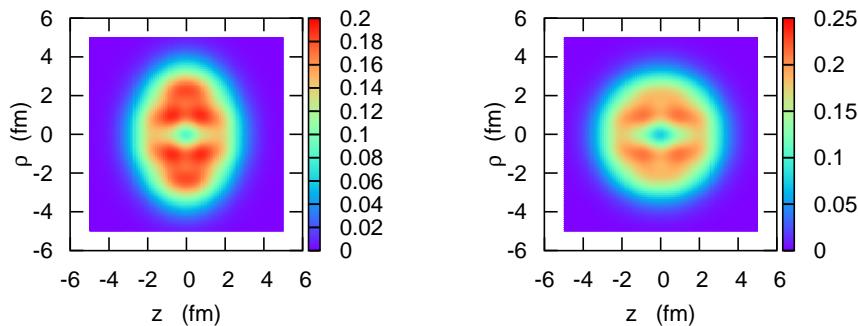


Fig. 2. The density profile for the ${}^{28}\text{Si}$ (the left panel) and for the ${}^{29}_{\Lambda}\text{Si}$ (the right panel) obtained with the RMF method. It is plotted with the cylindrical coordinate (z, ρ) , where the z axis is the symmetry axis. The unit for the density is fm^{-3} .

deformation parameter for the even-even core nuclei, while the solid line is for the corresponding hypernuclei. We see that the deformation parameter for the ${}^{28,30,32}\text{Si}$ nuclei is drastically changed when a Λ particle is added, although the change for the other Si isotopes is small. That is, the ${}^{28,30,32}\text{Si}$ nuclei have oblate shape in the ground state. When a Λ particle is added to these nuclei, remarkably they turn to be spherical. The corresponding density profile for ${}^{28,28+\Lambda}\text{Si}$ is shown in Fig. 2. The potential energy surfaces

for the $^{28,28+\Lambda}\text{Si}$ nuclei are shown in Fig. 3. The energy surface for the ^{28}Si nucleus shows a relatively shallow oblate minimum, with a shoulder at the spherical configuration. The energy difference between the oblate and the spherical configurations is 0.754 MeV, and could be easily inverted when a Λ particle is added.

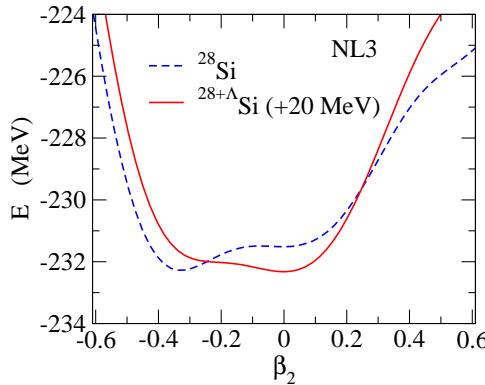


Fig. 3. The potential energy surface for the ^{28}Si (the dashed line) and $^{28+\Lambda}\text{Si}$ (the solid line) nuclei obtained with the constrained RMF method with the NL3 parameter set. The energy surface for $^{28+\Lambda}\text{Si}$ is shifted by a constant amount as indicated in the figure.

3. Mesonic decay of neutron-rich Λ hypernuclei

Let us next discuss the pionic decay of neutron-rich Λ hypernuclei. To this end, we use the formalism given in Ref.,¹⁴ where the standard Hamiltonian for the pionic decay of Λ particle is evaluated with single-particle wave functions obtained with a mean-field approximation. Here, we use the Skyrme-Hartree-Fock method with SIII parameter set.¹⁵ As for the ΛN interaction, we use the parameter set No. 1 given in Ref.² The pairing among nucleons is taken into account in the BCS approximation with a density-dependent contact interaction. Continuum states are discretized within a large box.

Figure 4 shows the pionic decay width for C isotopes obtained in this way. The final state interaction of pion is not taken into account. The dashed and dotted lines show the decay width for the proton ($\Lambda \rightarrow p + \pi^-$) and the neutron ($\Lambda \rightarrow n + \pi^0$) modes, respectively. The total width is denoted by the solid line. These are plotted in unit of the total decay width of a free Λ particle, $\Gamma_{\text{tot}}^{(\text{free})} = 2.50 \times 10^{-12}$ MeV. One sees that the decay width for the

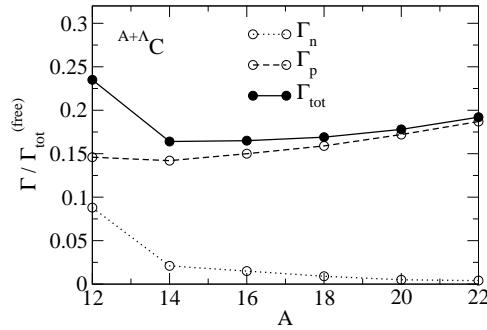


Fig. 4. The pionic decay width for C hypernuclei obtained with the Skyrme Hartree-Fock method. The dotted and dashed lines are for the neutron and the proton modes, respectively, while the solid line shows the total width. These are plotted in unit of the total decay width of a free Λ particle, $\Gamma_{\text{tot}}^{(\text{free})} = 2.50 \times 10^{-12}$ MeV.

neutron mode is suppressed due to the Pauli principle, as expected. On the other hand, that for the proton mode is increased in neutron-rich nuclei. A similar conclusion has been obtained also with shell model calculations.¹⁶

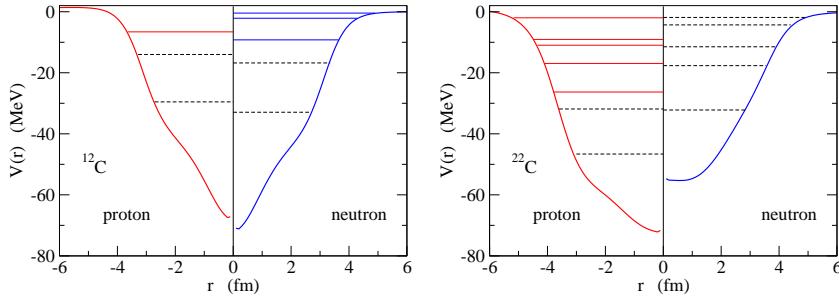


Fig. 5. The single-particle potentials for ^{12}C (the left panel) and for ^{22}C (the right panel). For each panel, the proton well is shown on the left hand side, while the neutron well is shown on the right hand side. The occupied levels are denoted by the dotted lines, while the unoccupied levels are denoted by the solid line.

This behaviour can be understood if we consider a change in the mean-field potential. Fig. 5 shows the single-particle potentials for $^{12,22}\text{C}$. The occupied and the unoccupied levels are denoted by the dotted and the solid lines, respectively. As the number of neutron increases, the proton mean-field potential is deepened whereas the neutron mean-field potential becomes shallower. This is because of a strong neutron-proton interaction.

As the proton single-particle potential well is deep, the number of bound (unoccupied) levels increases. At the same time, the momentum of the emitted pion increases. Both of these facts result in the enhancement of pionic decay width in neutron-rich nuclei, as shown in Fig. 4.

4. Summary

We have first used the relativistic mean field (RMF) theory to investigate quadrupole deformation of Λ hypernuclei. We have shown that, while an addition of Λ particle does not influence much the shape of many nuclei, ^{28}Si makes an important exception. That is, we have demonstrated that the Λ particle makes the shape of this nucleus change from oblate to spherical. In the second part, we investigated the pionic decay of neutron-rich Λ hypernuclei. We have shown that the neutron mode is largely Pauli-suppressed as the number of neutron increases, while the decay width for the proton mode increases. We have argued that this is because the proton mean-field potential is deepened in neutron-rich nuclei.

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